U.S. Department of Energy
Office of Nuclear Energy, Science and Technology
Advanced Fuel Cycle Initiative (AFCI)
Comparison Report, FY 2005

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Advanced Fuel Cycle Initiative (AFCI) Comparison Report

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TABLES

I. INTRODUCTION

Language in the Conference Report (House Report 108-10) accompanying the Fiscal Year (FY) 2003 Energy and Water Development Appropriations Act (see Appendix A) requires the Department to submit to Congress each year a report from the Advanced Fuel Cycle Initiative (ACFI) that will provide qualitative and quantitative information to enable Congress to compare the various strategies and technology approaches to managing commercial spent nuclear fuel. This document provides the Department's required report for FY 2005, with the same format as the FY 2004 report.

The AFCI program addresses critical national needs associated with past, current, and future use of nuclear energy – to increase the sustainability of nuclear energy. First, the AFCI is developing technologies that have the potential to allow more efficient disposition of commercial spent fuel and high-level waste, thus delaying the need for additional geologic repositories into the next century. Second, all AFCI fuel cycles would incorporate more proliferation-resistant technologies and designs than employed in current international practice, would reduce the inventory of weapons-usable material, and would eventually reduce the need for uranium enrichment. Third, in conjunction with the complementary Generation IV Nuclear Energy Systems Initiative, the AFCI investigates fuel cycles that would convert waste liabilities into energy source assets, ensuring that uranium ore resources do not become a constraint on nuclear energy. While accomplishing these objectives, the AFCI program also seeks to ensure competitive economics and excellent safety for the entire nuclear fuel cycle.

This document begins in Section I with the program's background, followed by explanation of the major AFCI objectives, and an overview of changes from the FY 2004 report. These provide the context for the comparison of fuel cycle strategies (Section II) and technologies (Section III) as requested by Congress. Per Congressional request, the comparisons contain substantial information and consideration of a full range of objectives and options. Section IV provides technological status and accomplishments. Section V provides a summary. Appendix A provides the legislative mandate for this report.

AFCI Program Background

The AFCI program evolved from the Office of Nuclear Energy, Science and Technology's Accelerator Transmutation of Waste (ATW) program, initiated in 1999. As a result of the research results produced by the ATW program and its successor, the Advanced Accelerator Applications (AAA) program, the AFCI program focuses on developing and demonstrating technologies that would enable the United States and other advanced countries to implement an improved, long-term nuclear fuel cycle that would provide environmental, nonproliferation, sustainability, economic, and safety advantages over the current once-through fuel cycle. This report addresses the degree to which various approaches would provide advantages versus once-through. These new technologies are intended to support the operation of current nuclear power plants (Generation II), new Generation III light water nuclear power plants, and Generation IV nuclear power plants.

The AFCI is part of a set of activities in the Department of Energy to develop nuclear energy technology and systems to enable a continuing role of nuclear power in domestic energy production. Within the Office of Nuclear Energy Science and Technology (DOE-NE), AFCI complements the Nuclear Power 2010 initiative to deploy new reactors in the next decade, the Generation IV program developing advanced reactor systems, and the Nuclear Hydrogen Initiative, which is coordinated with the Office of Energy Efficiency and Renewable Energy (DOE-EE). AFCI efforts also have important connectivity with geologic repository development within the Office of Civilian Radioactive Waste Management (DOE-OCRWM) and portions of the National Nuclear Security Administration (DOE-NNSA) that deal with global nuclear nonproliferation and safeguards.

AFCI Objectives

The AFCI's fundamental objective is to provide technology options that would enable long-term growth of nuclear power to improve environmental sustainability and energy security.

Nuclear energy's growth, and thereby its contribution to improving sustainability and energy security, can be enhanced by technology development aimed at the key areas of waste management, proliferation resistance, nuclear fuel utilization, economics, and safety. Thus, AFCI technology development focuses on reducing the long-term environmental burden of nuclear waste, improving proliferation resistance, and enhancing the use of nuclear fuel resources. The program has one major objective associated with each of these three considerations, which are described below. The AFCI program also has a fourth "system management" objective that emphasizes safe and economic nuclear materials management.

The AFCI provides an alternative to building multiple geologic repositories while still supporting an expanding role for nuclear energy. In short, that alternative is to reduce, reuse, and recycle.

An AFCI near-term goal is to provide relevant technical information to inform the Secretary of Energy regarding the potential need for additional geologic repositories. Current legislation requires the Secretary to make a report to Congress on the need for a second repository as early as January 1, 2007, but before January 1, 2010. DOE-OCRWM is responsible for drafting that report and is working closely with the AFCI program.

Objective 1. Reduce the long-term environmental burden of nuclear energy through more efficient disposal of waste materials.

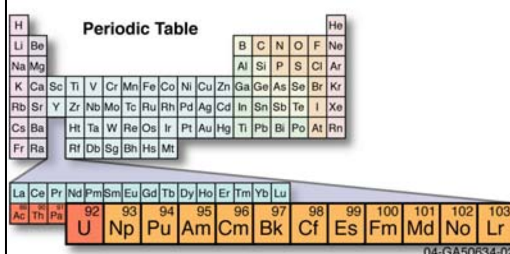
Under all strategies and scenarios for the future of nuclear power, the United States will need to establish a permanent geologic repository to deal with radioactive wastes resulting from the operation of nuclear power plants.

The geologic repository site at Yucca Mountain, Nevada, has the technical capability to accommodate all the U.S. commercial spent nuclear fuel that has been or will be generated by the current fleet of U.S. nuclear power plants. If relicensing extends all of these plants' lifetimes 20 more years, from 40 years to 60 years, the projected cumulative spent fuel will be approximately

120,000 metric tonnes. While the statutory limit for Yucca Mountain is 70,000 metric tones, a limited geologic exploration of the area has indicated the capability of accommodating at least 120,000 tonnes[1] .

Should a significant number of new nuclear plants be built in the future, the United States would need to construct at least one additional repository to address the additional wastes from the new nuclear plants or begin recycling of spent fuel to reduce the amount and longevity of nuclear waste. Even under conservative scenarios that assume merely the replacement of existing nuclear plants by new nuclear plants, at least one and as many as three additional repositories could be required by 2100. Scenarios that postulate a growing energy market share for nuclear power could require up to 20 repositories, each with an assumed capacity of 70,000 metric tonnes,[2] by 2100.

What are Transuranics?



Transuranics are elements in the periodic table with atomic numbers higher than uranium (element 92).

Why do they matter?

Transuranics affect repository performance by dominating long-term heat load and long-term radiotoxicity.

Transuranics and enriched uranium are the only materials of concern for proliferation.

Transuranics can be destroyed while producing extra energy if recycled in nuclear reactors.

The primary transuranics of interest to the AFCI program are neptunium (Np), plutonium (Pu), americium (Am) and curium (Cm).

Because of their technical, economic, and political challenges, geologic repositories are a significant consideration affecting the use of nuclear energy. Uranium in spent nuclear fuel dominates the mass and volume of packaged waste. The technical limits on geologic repository capacity could include long-term heat load and long-term peak doses from hypothetical releases of radioactivity from the waste; these characteristics are dominated by **transuranic elements** – neptunium, plutonium, americium, and curium (see sidebar). AFCI options exist to permit separation of uranium and transuranic elements from spent fuel. The uranium can either be recycled into new fuel or disposed as low-level waste via near-surface burial, as depleted uranium is disposed today. Transuranic elements can be recycled for **transmutation** (see sidebar next page) in reactors. Cesium and strontium are key short-lived fission products that are major contributors to heat in the first few decades after spent fuel leaves a reactor. Cesium and strontium could be kept in storage for up to three hundred years, and then disposed in ways that short-lived waste is disposed today, near-surface burial. Technetium and iodine are key long-lived fission products; they would likely be converted to durable waste forms and disposed in a geologic repository, but transmutation is also an option. By separating the elements in spent fuel and recycling what can be

[1] *Yucca Mountain Science and Engineering Report*, U.S. Department of Energy, Office of Civilian Radioactive Waste Management, DOE/RW-0539, May 2001. *Final Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada*, DOE/EIS-0250, February 2002.

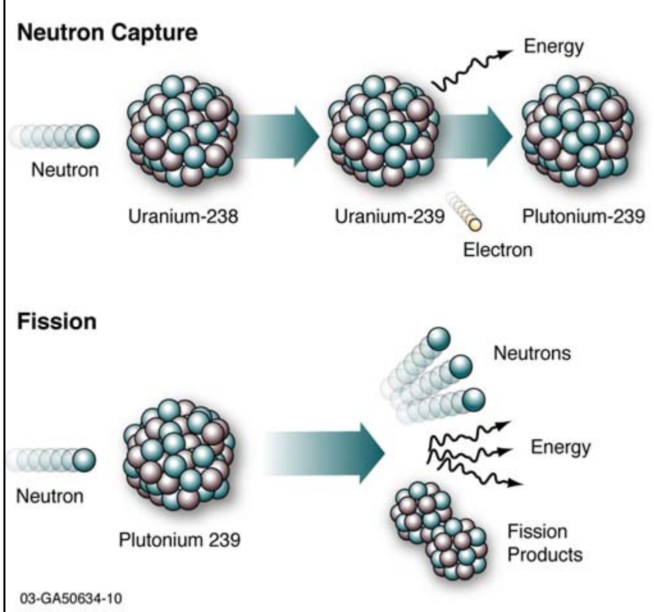
[2] 7,000 metric tonnes of the first repository is reserved for other high-level waste.

recycled, AFCI aims to defer the need for a second geologic repository at least until the next century and reduce the longevity of residual waste hazards.

Objective 2. Enhance overall nuclear fuel cycle proliferation resistance via improved technologies for spent fuel management.

The second objective of the program is to reduce the proliferation potential associated with the weapons-usable materials inherent in spent fuel. This includes both reductions in these materials in storage and in waste streams as well as improvements in monitoring and instrumentation during spent fuel processing and fabrication of recycled fuels. An important part of this objective is the development of more proliferation-resistant recycling technologies that could be adopted worldwide.

What is Transmutation?



Transmutation is the conversion of one isotope into another by changing its structure.

Quantitative proliferation resistance goals that support this objective include:

- In the short-term, develop fuel cycle technologies that enhance the use of intrinsic proliferation barriers.
- In the short-term, demonstrate the capability to eliminate more than 99.5 percent of transuranic weapons-usable materials from waste streams destined for direct disposal by destroying these materials through recycling.
- In the long-term, stabilize the inventory of weapons-usable material in storage by consuming it for sustained energy production.

Objective 3. Enhance energy security by extracting energy recoverable in spent fuel and depleted uranium, ensuring that uranium resources do not become a limiting factor for nuclear power.

Uranium resources are currently plentiful and uranium purchase price represents only a few percent of the cost of nuclear-generated electricity. However, the size of the uranium ore resource base is uncertain because there has been little incentive in recent decades to explore. As nuclear energy continues to expand globally and current stockpiles are used, technological options may be required to ensure domestic energy security against resource depletion.
Today's fuel cycle uses about one percent of the theoretical energy content in uranium ore. Direct disposal of spent fuel discards the energy content remaining in such fuel (plutonium, uranium, *etc*.).

Further, current nuclear power plants cannot use the uranium that is “depleted” and discarded after enrichment of natural uranium ore to make current types of fuel. There are two basic types of nuclear power plants. Thermal reactors, the predominant plant design at present, use enriched uranium and certain isotopes of the transuranic elements, called “fissile” isotopes. Fast reactors can extract energy from all of the uranium, including depleted uranium, and all isotopes of the transuranic elements. Section III provides more explanation of thermal and fast reactors.

To appreciate the theoretical energy content of existing nuclear waste, consider that the United States currently produces around 450 gigawatt-years of electricity annually from all sources. Commercial spent fuel now in interim storage contains 50,000 metric tons of uranium. Assuming one metric ton of uranium can produce approximately one gigawatt-year of electricity (if fully consumed), 50,000 metric tons of uranium is equivalent to more than 100 years of domestic total electricity generation. The United States is currently storing an additional 470,000 metric tons of depleted uranium (from which energy is recovered by transmuting its U_{238}), sufficient for 1,000 years of electricity generation at current rates. AFCI technology and Generation IV fast reactors could be employed to ensure that known domestic uranium resources are adequate well beyond this century to both sustain nuclear energy and reduce dependence on other energy sources.

Objective 4. Improve fuel cycle management, while continuing competitive fuel cycle economics and excellent safety performance of the entire nuclear fuel cycle system.

This objective has three goals – competitive economics, excellent safety performance, and overall system management.

Continue Competitive Economics: The economics of the nuclear fuel cycle is an essential component in any consideration of the future of nuclear power.

With most existing nuclear plants have almost fully depreciated their capital costs, [7] the average operating and maintenance cost of electricity from current U.S. nuclear plants is less than $0.018/kilowatt-hour, or 18 mills per kilowatt-hour (mills/kWhr). Projections for new plants in the next decade range from 47 to 71 mills/kWhr.[7] Fuel cycle costs are about 6 mills/kWhr.[7] Of this, 1 mill/kWhr is the fee paid by utilities to the Federal government for future geologic disposal, covering projected disposal costs. As experience is gained with the Yucca Mountain project, the actual costs for geologic disposal will become better known.

Continue Excellent Safety Performance: Safety and reliability are critical to all nuclear facilities. All new civilian nuclear facilities deployed in the United States will be licensed by the Nuclear Regulatory Commission and must meet rigorous safety requirements. By learning from past experience and improving technologies, any future fuel cycle facilities resulting from AFCI research will be at least as safe as current technology.

Well designed reactors have achieved exceptional levels of safety. Advances in reactor design, whether in terms of evolutionary improvement (Advanced Light Water Reactors) or systems such as those developed under the Generation IV initiative, aim towards consistent improvement in safety. Advanced fuel cycle technologies and systems are also being developed to achieve the highest levels of safety and to minimize exposures to workers and to the general public.

Improve fuel management to reduce storage at nuclear power plants: After discharge from current light water reactors, spent fuel must be stored in cooling pools for several years while short-lived fission products decay. This cooling period is necessary to reduce heat loads during subsequent spent fuel shipment to a geologic repository for disposal.

Some spent fuel is currently being stored well beyond the time needed for cooling while the geologic repository is in the licensing progress. Once the repository is opened, prolonged storage will end. However, due to license extensions current reactors are projected to generate more spent fuel than the legislated capacity of the first repository. Thus, timely disposition of spent fuel from current and future reactors may again be delayed during siting and licensing of additional repositories.

A long-term goal of AFCI is to enable an improved fuel cycle management system that would allow timely removal of spent fuel from nuclear power plants. Instead of direct disposal, spent fuel would be shipped to reprocessing facilities for recycling. Advanced fuel cycle recycling will sufficiently reduce the amount of material disposed as high level waste that siting and licensing of additional repositories can be avoided for at least 100 years. Once in place, the combination of one geologic repository and AFCI technologies will enable routine shipment of spent fuel after cooling is complete.

Changes from the FY 2004 Comparison Report

The current report keeps the same structure, format, and approach as in FY 2004 – with two enhancements. First, the program's objectives have become clearer and more quantitative.[3] This has improved the basis for comparing strategies and technology options. Second, deeper appreciation has been gained in the last year on the dynamic nature of fuel cycles – evolving from the *status quo* to one of many possible future scenarios. As a result, the program's four fuel cycle strategies have been adjusted to better illustrate how fuel cycles may evolve: first once-through, start limited recycle, move into transitional recycle, and eventually achieve sustained recycle.[4] These strategies are defined in Section II.

The research and development conducted during the last year permits an improved comparison of options versus the AFCI objectives. This is a required step before narrowing the range of options in the future. We are gaining increased confidence that there are practical ways to accomplish the

[3] *Report to Congress: Advanced Fuel Cycle Initiative, Objectives, Approach, and Technology Summary*, Prepared by the U.S. Department of Energy, Office of Nuclear Energy, Science, and Technology, May 2005.

[4] In contrast, in FY 2004, the strategies were tied directly to technologies – once-through, recycle in thermal reactors, recycle in a mixture of thermal and fast reactors, and recycle in fast reactors only.

major AFCI objectives. Future work will further increase confidence in potential solutions, optimize solutions for the objectives, and develop attractive development and deployment paths for selected options. This will allow the United States to address nearer-term issues such as avoiding the need for additional geologic repositories while making nuclear energy a more sustainable energy option.

Current Comparison

As in FY 2004, the current comparison comprises four tables:

Table 1 illustrates how separation, reactor, and fuel technologies combine to create strategies and options that address AFCI objectives. Tables 2, 3, and 4 provide more information on separation, reactor, and transmutation fuel options, respectively.

While the tables show a number of options, only the most promising are the focus of current AFCI research. The additional entries demonstrate the breadth of options considered and include alternatives that may be investigated in more depth in the future if research uncovers performance issues in the currently preferred technologies. Systems analysis studies will combine research results with industry trends to narrow the options to be considered for scale-up development. A summary of AFCI research status and future plans is provided in the last section of this report.

II. COMPARISON OF ADVANCED FUEL CYCLE STRATEGIES

Advanced fuel cycle planning focuses on four possible strategies. In this context, a strategy is a general approach to fuel management that encompasses a range of options with similar basic characteristics. A strategy identifies which materials are recycled (if any), the type of nuclear power plant, the type of spent fuel processing technology, and which materials go to geologic disposal.

- The current U.S. strategy is **once-through -** all the components of spent fuel are kept together and eventually sent to a geologic repository.
- The second strategy is **limited recycle**, recycling transuranic elements once. Remaining transuranic elements and long-lived fission products would go to geologic disposal. Uranium in spent fuel, depleted uranium, and short-lived fission products would be disposed as low-level waste. This strategy uses existing types of nuclear power plants, which are all thermal reactors.
- The third strategy is **transitional recycle**, recycling transuranic elements from spent fuel repeatedly until destroyed. Transitional recycle is more technically challenging than limited recycle and therefore more research, development, and deployments would be required. Uranium in spent fuel can be recycled or disposed. Essentially no transuranic elements would go to geologic disposal. Long-lived fission products would either go to geologic disposal or some could be transmuted in power plants. Short-lived fission products would be disposed as low-level waste. This strategy would primarily use thermal reactors; however, a small fraction of fast reactors may be required.
- The fourth strategy is **sustained recycle**, which differs from transitional recycle primarily by enabling the recycle of depleted uranium to significantly extend fuel resources. This strategy would primarily use Generation IV fast reactors.

This report does not address timing and evolution of strategies, which are addressed in the report, *Report to Congress Advanced Fuel Cycle Initiative: Objectives, Approach, and Technology Summary*.[8] That report notes two strategic timing goals:

- Develop and make available for industry the separations technology needed to deploy by 2025 a commercial-scale spent fuel treatment facility capable of separating transuranics in a proliferation resistant manner for their recycle and destruction via transmutation.
- Develop and make available the fuels technology needed for commercial deployment by 2040 of fast spectrum reactors operating either exclusively as transuranic transmuters or as combined fuel breeders and transmuters. Actual decisions to deploy fast reactors will, of course, be made by industry in response to market needs.

These strategic goals are the AFCI program's essential contributions to keeping open the option to rely on nuclear power for a portion of the nation's energy needs through the end of the twenty-first century and beyond. The first strategic goal would enable shift from the recycle strategy to the any of the recycle strategies noted above. The second strategic goal would enable the sustained recycle strategy and the fast reactor component of transitional recycle.

To help reach its strategic goals, the AFCI program has developed four programmatic objectives that guide its research,[9] which were discussed in Section I of this report and which provide the basis for comparison of strategies and technologies in Sections II and III. The comparisons also address the readiness of technologies for potential deployment. The technology readiness levels that are the target of current research for the key technologies for each option are as follows:

- Concept Development – The concept is still at a basic level. Suitable options for various applications are defined based on first principles and fundamental knowledge, with the critical technical issues or "showstoppers" identified, a work-around for showstoppers defined, and a verification plan developed.
- Proof of Principle – The concept has been shown to be technically feasible, but performance characteristics for operational plant performance are uncertain. Development is performed using laboratory scale experiments and analytic extrapolations to full-scale behavior.
- Proof of Performance – The concept is known to be technically feasible and there is considerable performance data, but scale-up to commercial scale is uncertain. Large-scale demonstrations on portions of the processes are performed, yielding final performance specifications, including statistical assessments and initial indications of economic performance.
- Commercial Experience – The technology has analogous commercial experience somewhere in the world and there is good understanding of economic performance.

Table 1 shows how the four strategies address the four objectives. Consistent with Congressional instruction for this report, the once-through fuel cycle is considered the *status quo*. The table is color-coded.

- In each row denoting an objective, strategies that meet the objective are shaded green. Strategies that partially meet the objective are yellow. Strategies that do not meet the objective are pink.
- For the four technology readiness levels, commercial experience is green, proof of performance is yellow, proof of principle is hatched yellow and pink, concept development is pink.

Under each of the four programmatic objectives in Table 1, there are several goals. "Short-term" refers to the period through 2025, when the program recommends the need for a commercially-deployed spent fuel treatment facility. "Intermediate-term" refers to the period from 2025 until the commercial availability of Generation IV fast spectrum reactors, projected to be about 2040. "Long-term" refers to the time after several of these fast reactors have been built.

Table 1. Comparison of Advanced Fuel Cycle Strategies

Strategy		Once Through		Recycle: Limited			Recycle: Transitional		Recycle: Sustained	Comment
Technology options that could implement strategy	Reactors	LWR	Thermal reactors, e.g., LWRs or VHTRs					Thermal reactors with 10-20% fast reactors	Fast reactors with 0-30% thermal reactors	LWR = Light Water Reactor VHTR = Very High Temperature Reactor
	Fuels	Uranium oxide (standard burnup)	High burnup uranium oxide for LWR (or oxycarbide for VHTRs)	Uranium-Pu mixed oxide (or oxycarbide)	TRU mixed oxide (or oxycarbide)	TRU IMF (or oxycarbide)	TRU IMF or mixed oxide (or oxycarbide)	TRU IMF or mixed oxide (or oxycarbide), then add fast reactor fuel	TRU metal, mixed oxide	IMF = inert matrix fuel (fuel without any uranium)
				Recycled fuels have 1 pass through reactor			Repeated passes	1 pass through thermal reactor, then transition to a thermal-fast reactor mix	Repeated passes	TRU = transuranic elements (Pu, Np, Am, Cm)
	Separations	none		PUREX [1]	UREX+			UREX+, pyroprocess	Pryoprocess, UREX+	PUREX = Plutonium-URanium EXtraction UREX+ = Uranium + TRU
Status - Illustrative technologies at each Technology Readiness Level										
Commercial experience (shaded green)		LWR, uranium oxide fuel	LWR	LWR, Pu mixed oxide fuel, PUREX	LWR					See definitions and color code in text.
Proof of performance (shaded yellow)			VHTR, high burnup uranium oxide	VHTR	VHTR, UREX+			Fast reactor, VHTR, UREX+		See Tables 2 (separations), 3 (reactors), and 4 (fuels) for information on technical readiness levels of individual technologies.
Proof of principle (hatched yellow/pink)			Uranium cxycarbide	TRU oxycarbide				TRU oxycarbide, fast reactor fuel, pyroprocess		
Concept development (shaded pink)					TRU mixed oxide	TRU IMF	TRU IMF or mixed oxide			
Objective 1. Reduce the long-term environmental burden of nuclear energy through more efficient disposal of waste materials.										
Reduce long-term heat load in geologic repository, need fewer repositories		Status quo	1.1 to 1.2x improvement			1.5 to 1.8x improvement	Up to 40x improvement	40x to 60x improvement		**Combined short-term and intermediate-term goal [2]**: Decrease long-term heat load to repository by 30x, delaying the need for additional geologic repositories by a century or more.
Reduce long-term radiation dose and radiotoxicity sources in geologic repository		Status quo, no reduction	Less than 3x reduction of long-lived radiation and dose sources. Stays more radiotoxic than natural uranium for more than 100,000 years.				Radiotoxicity reduced by 100x after 500 years in repository. At that time, waste becomes less radiotoxic than natural uranium.			**Intermediate-term and long-term goal**: reduce the long-lived radiation dose sources by a factor of 10 and radiotoxicity by a factor of 100, simplifying the design of the repository.
Objective 2. Enhance overall nuclear fuel cycle proliferation resistance via improved technologies for spent fuel management.										
Enhance the use of intrinsic proliferation barriers		Status quo - At discharge, high gamma, high heat rate. However, such self-protecting attributes decay significantly in the first century after discharge. Low neutron emission.		Low gamma, heat rate, and neutron emission	Inclusion of Np, Am, or Cm makes detection easier via isotopic signatures. Inclusion of Am or Cm increases gamma (easier detection, more hazardous handling). Inclusion of Am or Cm increases heat rate (more difficult weapon design). Inclusion of Cm increases neutron emission (detection may be more difficult, more hazardous handling, more difficult weapon design).					**Short-term goal:** develop improved technologies that may displace existing technologies.
Incorporate superior monitoring and materials accountability		Status quo - existing technologies provide substantial protection.			Improved monitoring technologies, taking advantage of inclusion of Np, Am, or Cm. "Safeguard by design," i.e., design of facilities such that any attempt to divert material is more difficult to accomplish ("tamper proof") or more easily detected.					
Reduce weapons-usable material from waste destined for geologic disposal		Status quo, all kept in waste	Reduces net weapons-usable production 20% (but kept in waste)	25% destroyed by recycling	30% destroyed by recycling	70% destroyed by recycling	>99.5% destroyed by recycling over multiple cycles			**Short-term goal**: eliminate 99.5% of weapons-usable material from waste.
Stabilize inventory of weapons usable material in storage		Status quo, inventory does not stabilize					Inventory stabilizes [3,4]			**Long-term goal**: reduce production, stabilize inventory.
Degree and amount of uranium enrichment technology required		Status quo	Slightly reduced due to higher burnup and/or recycle						Uranium enrichment not needed	Near-term proliferation risk may be dominated by spread of existing uranium enrichment technology.
Objective 3. Enhance energy security by extracting energy recoverable in spent fuel and depleted uranium, ensuring that uranium resources do not become a limiting factor for nuclear power.										
Relative energy recovery from uranium ore		Status quo, discard spent nuclear fuel	Slight improvement due to higher burn-up	Up to 1.3x improvement			Up to 2x improvement	2-10x improvement, depending on thermal-fast reactor mix	50-100x improvement	**Short-term goal**: 1.15x more energy than once-through **Long-term goal**: 50x improvement
Objective 4. Improve fuel cycle management, while continuing competitive fuel cycle economics and excellent safety performance of the entire nuclear fuel cycle system.										
Economic indicators	Cost of additional repositories	Status quo - beyond Yucca Mtn, 3 to 21 repositories needed this century depending on nuclear growth		10-20% fewer repositories than status quo, smaller waste volume		30-40% fewer repositories, smaller waste volume	No additional repositories needed			Cost of additional geologic repositories is uncertain, and not being studied.
	Benefit from producing hydrogen	Status quo, temperatures inadequate	Depends on VHTR entry into the future hydrogen production market						VHTR limited, most reactors must be fast	Hydrogen production may be a new market for nuclear power, comparable in magnitude to electricity production
	Need for new reactor types	Status quo, none required	Either LWR or VHTR could be used. VHTR would only be used if economic for electricity and/or hydrogen production.[5]					Fast reactors are required, but cost is uncertain.[6]		New reactor and fuel cycles may be more expensive than current types. Separation costs uncertain. Costs of new systems are being studied by AFCI and Generation IV programs.
	Fraction of spent fuel that is separated	Status quo, none required		85-90%		90-95%	100%			
	Fraction of fuel that uses recycled material	Status quo, none required		10-15%		5-10%	10-35%		100%	
Safety indicators	Use Generation IV reactors with enhanced safety	Status quo	LWR - evolutionary improvements only VHTR is a Generation IV concept with improved methods of decay heat removal, more robust fuel, and chemically inert coolant					VHTR and fast reactors are Generation IV concepts with various safety enhancements		A key Generation IV goal is increased reactor safety characteristics
	Minimize transport of spent and recycle fuels (considering both distance and mass flows)	Status quo	Transportation of SNF is 50% of once-through if burnup doubles.	Transport is similar to once-through for the same burnup, depending on location of separation-fuel fabrication plant, repository, and power plants.			With off-site recycling at 1.5-year fueling intervals, transport is 100-200% of once-through depending on facility locations. Either battery-type reactors (30-year fueling intervals) or onsite recycling reduce transport to 1-10% of once-through			Relative importance of transportation to be determined.
Reduce on-site storage at nuclear power plants		Status quo	Removal rate unchanged, but accumulation cut in half because of higher burnup	In parallel to filling first geologic repository, can double the rate of removal of spent fuel at power plants by opening first recycling plant. However, need for additional repositories will inhibit meeting goal.			Because no additional repositories needed, storage at nuclear power plants will cease to be a problem.			**Long-term goal**: storage time no more than 5 years
Color code		Pink = strategies that do not meet each objective		Yellow = strategies that partially meet objective				Green = strategies that meet each objective		

[1] PUREX information is provided for comparison purposes only; this option is not being considered in the AFCI program.
[2] This is the combined impact of 3 goals - (a) remove 99.5% of transuranic elements from waste, each pass through the recycle plant, (b) separate cesium and strontium from waste destined for geologic disposal, and (c) reduce transuranic elements in emplaced waste by 100x.
[3] Curium may be held in storage to avoid accumulation of isotopes that are strong gamma and neutron emitters. If so, options are (a) wait for Cm-244 decay (18.1-year halflife) then re-introduce to fuel cycle, (b) transmute in fast reactors, (c) transmute in an Accelerator Driven System, or (d) send to geologic disposal. Putting curium in geologic disposal would not substantially harm repository benefits.
[4] The stabilization level of weapons-usable inventory depends on reactor mix, conversion ratio, etc.
[5] VHTRs are not required in these strategies. Thus, there is little fuel cycle cost impact if VHTRs prove to be more expensive than LWRs; they simply will not enter the electricity market.
[6] If fast reactors are more expensive than LWRs/VHTRs, government incentives may be required to promote construction of the required number of fast reactors.

As one progresses through the four strategies (left to right in the table), the better the achievement of objectives 1, 2, and 3. However, objective 4 (economics, safety, and system management) complicates the picture. In economics, a trade-off occurs between the economic uncertainty of requiring additional repositories (left side of the table) versus the economic uncertainty for fuel strategies that require new reactor types (right side of the table). There is one option (transitional recycle with LWR) that does not require either new repositories or new reactor types, but there are technical issues regarding whether this option will work and (if so) its performance relative to other options. As shown later in Table 2 (separation technologies), Table 3 (reactor technologies), and Table 4 (fuel technologies) the technologies required to implement the strategies (as one moves right in Table 1) are at a less mature stage of technology development.

All of the recycle strategies represent lower technology readiness and hence more need for research and development compared to the once-through fuel cycle. This is most true for the recycle strategies that include fast reactors with their fuels and separation technologies.

Objective 1. Reduce the long-term environmental burden of nuclear energy through more efficient disposal of waste materials.

By working together, separation, transmutation, and fuel technologies provide complete energy systems that can reduce the long-term environmental burden of waste compared to the current "once-through/no separation" approach. Each recycle strategy addresses the four major components of spent fuel - uranium, transuranic elements, short-lived fission products, and long-lived fission products.

- All AFCI recycle options separate uranium to reduce the mass and volume of waste and possibly the number and cost of waste packages that require geologic disposal. Separated uranium can either be managed with the same method (near-surface burial) as used for the much larger quantities of depleted uranium or recycled into new reactor fuel.
- All AFCI recycle options provide means to recycle at least plutonium (Pu) and neptunium (Np). Some also recycle the other two transuranic elements - americium (Am) and curium (Cm). The United States is not pursuing any option that would separate plutonium by itself.[5] By consuming transuranic elements that would otherwise go to a geologic repository, recycling offers the potential to increase geologic disposal capacity (in the sense of accommodating the waste from more reactor-years worth of energy generated), decrease the long-term waste burden, and extract more energy from a given quantity of the original uranium ore resource.
- All AFCI recycle options provide the capability to separate short-lived fission products cesium and strontium to allow them to decay in facilities tailored to that need, rather than complicate long-term geologic disposal. This can also reduce the number and cost of waste

[5] *National Energy Policy – Report of the National Energy Policy Development Group,* May 2001. Pages 5-17 and 5-22 that "the United States will continue to discourage the accumulation of separated plutonium, worldwide."

packages requiring geologic disposal. These savings may be offset by costs for separation, recycle, and storage systems.

- All AFCI recycle options lead to long-lived fission products, such as technicium-99 and iodine-129, going to geologic disposal in improved waste forms. However, the program has not precluded their transmutation as a future alternative.

Number of repositories needed: The legislated initial capacity of the first geologic repository per the Nuclear Waste Policy Act is 70,000 metric tonnes; an increase in capacity of a factor of two by physical repository expansion would ensure sufficient repository capacity if all current nuclear power plants' lifetimes are extended 20 years, from 40 to 60 years, and no new power plants are built.

If nuclear power continues throughout this century at no growth, level market share, or market gain (growth rates of 0.0, 1.8, or 3.2 percent per year respectively), then fuel discharged by 2100 would necessitate increases in geologic repository capacity of factors of 4, 9, or 20 to avoid the need for a second geologic repository. (These numbers relate to the *status quo* - current types of fuel, current uranium enrichment, and current burnup.) These increases (4, 9, or 20) must be met by physical expansion of the first repository, by siting additional repositories, by recycling, or by a combination of all three.

Thus, assuming nuclear power continues throughout this century, the *status quo* could lead to the need for between four and twenty geologic repositories by 2100, each assumed to have capacity for 70,000 metric tonnes. Since there seems to be little prospect for physical expansion of the first repository by the factors projected above, spent fuel must be recycled to avoid the need for a number of additional repositories.

Limited recycle offers the potential for an improvement of a factor of four, for example by combining three possibilities - high burnup fuels (improvement repository capacity by a factor of 1.2), one pass of inert matrix fuel (improvement factor of 1.8), and doubling the physical capacity of the first repository. This would give a combined factor of about four, which might be adequate for the no-growth case (declining market share). In all other cases, high-burnup or limited recycle can help, but would not meet the objective to defer a second repository until the next century. Limited recycle would nonetheless provide additional flexibility for the first repository to meet disposal needs before more advanced technologies (transitional or sustained recycle) become available.

In contrast, transitional or sustained recycle should be able to meet this critical objective, achieving much higher repository capacity improvement factors.

Duration of waste hazards: Another issue is the long time period of stewardship for spent fuel. This is driven by the time necessary for radioactive decay of waste constituents, which varies by isotope from a few years to more than a million years. Successful application of AFCI technologies and Generation IV power plants can achieve large reductions in the longer-lived transuranic isotopes remaining in radioactive wastes sent to geologic disposal. If only fission products are disposed, the time frame for human responsibility is several centuries, rather than several hundreds of thousands of years.

The *status quo* leads to waste that remains more radiotoxic than the original natural uranium ore for hundreds of thousands of years, although safe geologic disposal protects the public from these wastes. Transitional or sustained recycle can change the geologic disposal time horizon from hundreds of thousands of years to several centuries, by recycling the transuranic isotopes. This changes transuranic isotopes from waste management liabilities into energy resource assets.

Objective 2. Enhance overall nuclear fuel cycle proliferation resistance via improved technologies for spent fuel management.

Current U.S. policy discourages the transfer of uranium enrichment and reprocessing technology to states that do not currently have established commercial fuel cycle infrastructure. The proliferation resistance goal for AFCI is to provide less attractive routes for proliferation than uranium enrichment. Likewise, physical protection systems for AFCI materials and infrastructure must prevent theft of materials as effectively as for other materials managed in the system.

Table 1 includes five indicators of proliferation resistance: intrinsic proliferation barriers, safeguard technologies, reducing weapons-usable material from waste destined for geologic disposal, stabilizing the inventory of weapons-usable material in storage, and need for uranium enrichment. These are relevant to differing degrees to the four threat strategies: **theft** of weapons-usable material, **clandestine diversion** of material from facilities that are declared under the Non-Proliferation Treaty, **clandestine production** in undeclared facilities, and **abrogation** of responsibilities under the Non-Proliferation Treaty by a nation state leaving the treaty.

Material theft: Many factors can potentially increase security against theft by terrorists and other subnational groups: (a) increasing the handling hazards of weapons-usable material throughout the fuel cycle relative to either pure plutonium or highly enriched uranium; (b) increasing the radiation field of weapons-usable material to make detection of stolen material easier than detection of plutonium or highly enriched uranium; (c) reducing inventories by consuming weapons-usable material via recycling, removing weapons-usable material from waste streams, and eliminating older spent fuel inventories before fission product radiation barriers drop; (d) closing a geologic repository making emplaced material much less accessible before fission product radiation barriers drop, (e) incorporating anti-theft features into facility and transport-system designs such as large physical barriers to access and support for effective deployment and response by guard forces; and (f) co-locating fuel separation and fuel fabrication facilities. (The "quality" of weapons-usable material may not be an important consideration for theft because the effects of an explosion of even a crude nuclear device would be unacceptable and therefore a possible terrorist objective.) The first four indicators in Table 1 (intrinsic barriers, safeguard technologies, inventory consumption, and inventory stabilization) are significant contributors to increasing security against material theft.

Clandestine diversion from declared facilities: AFCI technologies can increase security against clandestine diversion by performing research and development leading to (a) material that is easier to detect by including neptunium or americium in recycled fuel, (b) improved monitoring technologies, (c) "safeguard by design," i.e., design of facilities such that any attempt to divert material is more difficult to accomplish ("tamper-proof") or more easily detected, and (d) by making use of diverted material more difficult by reducing the "quality" of weapons-usable material. (Poor "quality" of weapons-usable material may be a barrier for nation states which presumably aim to have a high-confidence nuclear weapon.) AFCI technologies will not produce any attractive direct-use material, neither highly enriched uranium nor weapons-grade plutonium. The first, second, fourth, and fifth indicators in Table 1 (intrinsic barriers, safeguard technologies, inventory stabilization, and uranium enrichment) are significant contributors to increasing security against clandestine division.

Clandestine production in undeclared facilities: No research and development program can destroy the existing knowledge of PUREX or uranium enrichment, which provide potential strategies toward proliferation. Potential proliferators can use such existing technologies in clandestine, undeclared facilities. Thus, the AFCI objective here is to "do no harm." AFCI technology would only be exported to fuel-cycle states with strong non-proliferation credentials and substantial nuclear expertise and infrastructure, including enrichment infrastructure. In the unlikely event that one of these states would decide to proliferate using clandestine production, the uranium enrichment route would be more attractive than the AFCI route. As AFCI technologies show their worth for commercial purposes, detection of manufacture, purchase, or use of technological equipment associated with PUREX would be a clearer signal of proliferation intent. The first, second, and fifth indicators in Table 1 (intrinsic barriers, safeguard technologies, uranium enrichment) provide some assistance in increasing security against clandestine production.

Abrogation: No research and development program can prevent a nation from abrogation of its responsibilities under the Non-Proliferation Treaty. Any fuel-cycle state with commercial uranium enrichment infrastructure would already have the ability to abrogate, and then to rapidly convert low enriched uranium into highly enriched uranium using its existing infrastructure. The addition of AFCI infrastructure would not provide any significantly more attractive routes for abrogation. The first, second, fourth, and fifth indicators in Table 1 (intrinsic barriers, safeguard technologies, inventory stabilization, and uranium enrichment) provide some assistance in increasing security against abrogation.

Thus, new AFCI technologies should offer:

- New technology that is developed in concert with new international systems to prevent recurrence of past problems. The new AFCI suite of technologies offers opportunities to reduce risks associated with material theft (by terrorist or sub-national groups), clandestine diversion from declared facilities (by nation states), clandestine production in undeclared facilities, and possibly abrogation of NPT responsibilities, as noted above.
- An increased likelihood that AFCI technologies will become the technologies of choice for fuel cycle states, displacing PUREX by virtue of their ability to address multiple programmatic objectives (repository capacity, repository dose, energy sustainability, safety, and economics). This provides a "clean slate" for technology control.

In summary, the *status quo* continues the abrogation of U.S. technological leadership, continued international use of the PUREX technology, and ever-increasing inventories of weapons-usable material in spent fuel. AFCI technologies can be designed to be proliferation-resistant when deployed into responsible fuel cycle states; AFCI technologies can be designed to support robust physical security measures to prevent any potential for theft of material.

Objective 3. Enhance energy security by extracting energy recoverable in spent fuel and depleted uranium, ensuring that uranium resources do not become a limiting factor for nuclear power.

The next part of Table 1 addresses sustainability and energy recovery. The energy content in uranium ore can be more effectively used as the energy content in spent fuel is recovered. Sustained recycling is needed to substantially improve energy recovery.

With the once-through strategy, only about 1 percent of the energy content in the original uranium ore is used; 99 percent is wasted. Eventually, uranium ore resources could become an issue. All components of spent fuel remain liabilities.

With limited recycle, there is a slight improvement; less than 2 percent of the energy content is used, more than 98 percent is wasted. Some of the transuranic elements are converted from a liability to an energy asset; everything else (including depleted uranium and uranium in spent fuel) remains a liability.

Transitional recycle can use about 10 percent of the energy content in the original uranium ore, but still wastes about 90 percent. The percentages depend on the mix of reactor types and the "conversion" ratio of reactors, defined in Section III. Transuranic elements are converted from waste liabilities to energy assets.

With sustained recycle, there is a substantial improvement; up to 99 percent of the energy content in the original uranium ore could be used. (The percentage depends on economics, process losses, *etc*.) Only ~1 percent of the energy content in uranium ore would be wasted because of cumulative losses through repeated recycle passes. Depleted uranium in existing low-level waste would be converted from waste liabilities to energy assets. Uranium ore resources would not become a constraint.

In summary, the *status quo* wastes the energy in spent fuel. Any of the recycle options recover some of that energy value. The sustained recycle strategy extracts the maximum energy value from the original uranium ore.

Objective 4. Improve fuel cycle management, while continuing competitive fuel cycle economics and excellent safety performance of the entire nuclear fuel cycle system.

Continue Competitive Economics: It is premature to provide comparative economic calculations because there are so many factors involved, many of which have high uncertainties. Table 1 does include several key indicators. These are not simply additive because they do not contribute equally to total fuel cycle cost impact. There is also the complication of having two potential nuclear power markets – electricity and hydrogen production.

There is a large economic uncertainty associated with the cost of additional geologic repositories. Indeed, the viability of the once-through fuel cycle requires establishing the viability (and cost) of siting and constructing additional geologic repositories.

The importance of cost uncertainties for the Generation IV thermal spectrum reactors (such as the Super-Critical Water Reactor (SCWR) and the Very High Temperature Reactor (VHTR)) is very different than for Generation IV fast reactors. From a fuel cycle perspective, there is relatively little difference between LWRs and Generation IV thermal reactors. The penetration of Generation IV thermal reactors into the current LWR market (electricity) and into the transportable energy fuel market (via hydrogen production) depend primarily on economics; in those contexts, the cost uncertainties associated with Generation IV thermal reactors are critical. But, from the fuel cycle perspective, strategies that work with Generation IV thermal reactors can also work without them. For example, both LWRs and Generation IV thermal reactors offer the potential to preferentially consume ("burn") transuranics with little or no uranium in the fuel, i.e., inert matrix fuel. Referred to as "deep burn", advocates of the VHTR in particular believe that their preferred technology can more easily and effectively achieve this than can LWRs. The effectiveness of such approaches depends on how long each type of inert matrix fuel can be kept in each type of reactor, which is the subject of ongoing research. Generation IV thermal reactors are not required to make any of the fuel cycle strategies work.

In contrast, the cost uncertainty of Generation IV fast reactors is very relevant to AFCI. At least one type of fast reactor or Accelerator-Driven System must be made economical for the sustained recycle strategy to be viable. The importance of fast reactor cost uncertainty to the transitional recycle strategy depends on the percent of fast reactors required to make the strategy work, which requires more analysis.

Separation costs are uncertain; all recycle strategies depend on separation. Table 1 shows that the amount of separation required does not vary greatly among the recycle options.

The costs of new fuels that can use recycled transuranic elements are uncertain; all recycle strategies require new fuels. However, Table 1 shows that the fraction of all fuel used that must be new varies considerably among the recycle options, ranging from 5-10 percent for limited recycle with inert matrix fuel to 100 percent for sustained recycle.

The economic uncertainty associated with limited recycle (excluding the potential cost of additional geologic repositories) is less than that of transitional and sustained recycle because no fast reactors are needed.

With transitional recycle, the economic uncertainty associated with additional geologic repositories is reduced, but economic uncertainties associated with new reactors increases for most options. If only thermal reactors are used, the practicality (hence cost) of transitional recycle is relatively uncertain. If fast reactors are added, the practicality of sustained recycle is not in doubt; but the cost penalty (if any) of fast reactors and their associated facilities is uncertain. Fast reactor development under the Generation IV program will determine its economic competitiveness.

With sustained recycle, there is no economic uncertainty associated with the need for new geologic repositories, but fast reactors and their associated facilities are required.

Continue Excellent Safety Performance: This objective must apply to the entire fuel cycle, including power plants. The safety of the entire system is likely dominated by the safety of the reactors, because they are more numerous than geologic repositories or recycling plants and because their fuel has a power density several factors of 10 higher than during other parts of the fuel cycle.

- With the once-through strategy, there will be at least one repository per 100 nuclear power plants, each assumed to be about 1 GWe capacity.
- With limited recycle, there will be slightly fewer repositories than once-through and about one recycle plant per 100 nuclear power plants.
- With transitional or sustained recycle, there will be one repository independent of the number of nuclear power plants. There will be either about one large centralized recycle plant per 100 nuclear power plants or decentralized recycling at each nuclear power plant.

This means that a complete assessment of fuel cycle safety must include the impact of new recycle fuel types on reactor operation. Indeed, reactor safety parameters are routinely included in exploring the appropriate composition of recycle fuels.

Improve fuel management to reduce storage at nuclear power plants: After discharge from current light water reactors, spent fuel must be stored in cooling pools for several years while short-lived fission products decay. This cooling period is necessary to reduce heat loads during subsequent spent fuel shipment to a geologic repository. Some spent fuel is currently being stored well beyond the time needed for cooling while the geologic repository is in the licensing process. There is already ~50,000 MT of accumulated spent fuel in storage at commercial nuclear plants. By the time the first geologic repository opens, there will be sufficient waste accumulated to exhaust its statutory capacity. It is possible that this pattern could continue – build geologic repositories after waste has accumulated – in which case significant interim storage inventories will persist. Alternatively, the rate of geologic repository construction could substantially accelerate.

With limited recycle, there is delay in the need for additional interim storage or geologic repositories because spent fuel would be recycled once. This creates time for either building interim storage or building additional geologic repositories.

With transitional or sustained recycle, there is a reduction in the need for interim storage as recycling plants are brought into operation. Spent fuel components would be routinely recycled, rather than stored.

III. COMPARISON OF ADVANCED FUEL CYCLE TECHNOLOGIES

This section provides more detail on the technology options corresponding to the strategies described in Table 1 (on page 16). The technology options are organized into three areas, with corresponding comparison tables:

Table 2. Comparison of Separation Technologies (page 23)
Table 3. Comparison of Reactor Technologies (page 25)
Table 4. Comparison of Transmutation Fuel Technologies (page 29)

The top rows of each technology table indicate the fuel cycle strategies supported by each technology. These strategies correspond to the main column headings in Table 1. Next, each table provides a technical compatibility crosswalk that ties it to the other two technology tables. These rows indicate the combinations of separation, reactor, and transmutation fuel technologies that could work together as part of a full fuel cycle option. The next section of each table provides information on the development status of the technology. The lower sections of the technology comparison tables provide indicators for the objectives described in Section I.

Comparison of Separation Technologies

The *status quo* is once-through (no separation) in the United States and commercial separation of plutonium in France and Japan. The primary purpose of plutonium separation is to recycle it, thereby recovering its energy content. The technology used by these commercial operations is PUREX, which separates plutonium from spent nuclear fuel. It was originally developed by the United States at Oak Ridge National Laboratory in the late 1940s. The 2001 National Energy Policy[6] recommends development of alternative reprocessing and fuel treatment technologies that reduce waste streams and enhance proliferation resistance and sharing these technologies with international partners with highly developed fuel cycles. In doing so, the United States hopes to improve advanced fuel cycle economics and waste management while discouraging the accumulation of separated plutonium.

Table 2 compares three advanced technologies – Uranium Extraction Plus (UREX+), the pyrochemical pyroprocess, and molten fuel salt treatment – against the direct disposal of spent fuel and PUREX.

[6] *National Energy Policy – A Report of the National Energy Policy Development Group*, May 2001.

Table 2. Comparison of Separation Technologies

<table>
<tr><th>Separation Option</th><th>None
(Status quo
in the United States)</th><th>PUREX [1]
(Status quo in
France, Japan, etc.)</th><th>UREX+</th><th>Pyroprocess</th><th>Molten Fuel+Coolant Salt Processing</th><th>Comments</th></tr>
<tr><td colspan="7">Strategies Supported</td></tr>
<tr><td>Once Through</td><td>Yes</td><td>---</td><td>---</td><td>---</td><td>Yes</td><td rowspan="2">Green = Yes
Pink = No</td></tr>
<tr><td>Any of the recycle strategies</td><td>---</td><td>Yes</td><td>Yes</td><td>Yes</td><td>Yes</td></tr>
<tr><td colspan="7">Compatible Reactor Options</td></tr>
<tr><td>Light Water Reactor (LWR)</td><td colspan="3">Yes</td><td>To be clarified [3]</td><td>---</td><td rowspan="3">These are thermal reactor options.</td></tr>
<tr><td>Very High Temperature Reactor (VHTR)</td><td>Yes</td><td colspan="2">Yes [2]</td><td>Yes</td><td>---</td></tr>
<tr><td>Supercritical Water Reactor</td><td colspan="3">Yes</td><td>To be clarified [3]</td><td>---</td></tr>
<tr><td>Molten Salt Reactor</td><td colspan="4">---</td><td>Yes</td><td>Can be either thermal or fast.</td></tr>
<tr><td>Sodium Fast Reactor</td><td>---</td><td colspan="3">Yes</td><td>---</td><td rowspan="2">These are fast reactor options.</td></tr>
<tr><td>Lead or Gas Fast Reactor</td><td colspan="2">---</td><td>Yes, for nitride fuel</td><td>Yes</td><td>---</td></tr>
<tr><td colspan="7">Compatible Fuel Options</td></tr>
<tr><td>Oxide (with or without uranium)</td><td colspan="3">Yes</td><td>To be clarified [3]</td><td>---</td><td rowspan="5">Green = Yes
White = see details
Pink = No</td></tr>
<tr><td>Carbide/oxycarbide [4]</td><td>Yes</td><td>---</td><td>Yes [2]</td><td>Yes</td><td>---</td></tr>
<tr><td>Metal</td><td colspan="3">---</td><td>Yes</td><td>---</td></tr>
<tr><td>Nitride</td><td colspan="2">---</td><td>Yes</td><td>Yes</td><td>---</td></tr>
<tr><td>Molten salt</td><td colspan="4">---</td><td>Yes</td></tr>
<tr><td colspan="7">Status</td></tr>
<tr><td>Technology Readiness Level</td><td colspan="2">Commercial Experience</td><td>Proof of performance</td><td>Proof of principle</td><td>Proof of principle</td><td>See definitions and color code in text.</td></tr>
<tr><td colspan="6">Objective 1. Reduce the long-term environmental burden of nuclear energy through more efficient disposal of waste materials.</td><td></td></tr>
<tr><td>Able to separate uranium</td><td>No</td><td colspan="4">Yes</td><td>Uranium dominates waste mass, which are factors in separation and waste packaging costs. Thus, uranium separation may reduce costs.</td></tr>
<tr><td>Able to separate transuranic elements</td><td>No</td><td>Not developed</td><td>Yes</td><td>Yes [3]</td><td>Yes</td><td>Pu, Np, and Am dominate long-term heat load, radiotoxicity, and hypothetical doses.</td></tr>
<tr><td>Able to separate cesium and strontium</td><td>No</td><td>Not developed</td><td>Yes</td><td colspan="2">Not developed</td><td>These dominate short-term heat load.</td></tr>
<tr><td>Able to separate technicium and iodine</td><td>No</td><td>Not developed</td><td colspan="3">Yes</td><td>After transuranics, these elements dominate long-term dose because they are relatively transportable.</td></tr>
<tr><td>High-level waste/year [5]</td><td>2,000 tonne heavy metal in spent nuclear fuel; 660 tonne cladding</td><td>490 tonne glass; 1,900 tonne uranium [6]</td><td>230 tonne glass [7]</td><td colspan="2">490 tonne ceramic waste form</td><td>In recycle strategies, most or all of the transuranic elements are recycled and are therefore high-level waste.</td></tr>
<tr><td>Low-level waste/year [5]</td><td>-0-</td><td>350 tonne raffinates & process materials; 660 tonne cladding</td><td colspan="2">1,900 tonne uranium; 660 tonne cladding; 10 tonne cesium-strontium waste</td><td>1,900 tonne uranium; no cladding; 10 tonne cesium-strontium waste</td><td>Waste from processing only. Does not include waste from uranium enrichment nor reactor operation. In some strategies, this uranium will be recycled.</td></tr>
<tr><td colspan="7">Objective 2. Enhance overall nuclear fuel cycle proliferation resistance via improved technologies for spent fuel management.</td></tr>
<tr><td>Avoid separation of weapons-usable elements with low intrinsic barriers to proliferation resistance</td><td>Yes</td><td>No (pure plutonium)</td><td colspan="3">Yes</td><td></td></tr>
<tr><td>Enable stabilization of weapons-usable inventories</td><td>No</td><td>No</td><td colspan="3">Yes, via transitional or sustained recycle</td><td></td></tr>
<tr><td colspan="7">Objective 3. Enhance energy security by extracting energy recoverable in spent fuel and depleted uranium, ensuring that uranium resources do not become a limiting factor for nuclear power.</td></tr>
<tr><td>Enable energy recovery from legacy spent fuel</td><td>No</td><td>Partial</td><td colspan="3">Yes</td><td>Virtually all legacy spent fuel is uranium oxide.</td></tr>
<tr><td>Enable energy recovery from depleted uranium</td><td>No</td><td colspan="2">Only for sodium fast reactors with oxide fuel</td><td colspan="2">Yes</td><td>Must support transitional/sustained recycle in fast reactors</td></tr>
<tr><td colspan="7">Objective 4. Improve fuel cycle management, while continuing competitive fuel cycle economics and excellent safety performance of the entire nuclear fuel cycle system.</td></tr>
<tr><td>Assists in continuing competitive nuclear energy economics?</td><td colspan="5">Depends on the system in which the technology is used, see Table 1.</td><td></td></tr>
<tr><td>Able to separate neutron-absorbing components from the transuranics to be recycled</td><td>No</td><td colspan="2">Yes</td><td>May not be sufficient for thermal reactors [8]</td><td>Not developed</td><td>Removal of these materials from recycled fuel improves fuel economic performance.</td></tr>
<tr><td>Assists in continuing excellent safety performance.</td><td colspan="5">All power, separation, and fuel plants will meet rigorous safety objectives and requirements.</td><td></td></tr>
<tr><td>Assists reducing storage of discharged fuel at power plants</td><td>No</td><td colspan="4">Yes</td><td></td></tr>
<tr><td>Color code for four objectives</td><td colspan="2">Pink = strategies that do not meet each objective</td><td colspan="2">Yellow = strategies that partially meet objective</td><td colspan="2">Green = strategies that meet each objective</td></tr>
</table>

[1] The PUREX estimates in this table are provided for comparison purposes only; this process is not being considered in AFCI planning.
[2] UREX+ can be applied to VHTR fuels if a grind-leach process can be applied.
[3] An approach for reducing oxide fuel to metallic form for treatment via pyroprocess has been demonstrated at small scale. However, it may be difficult to separate neutron-absorbing elements from recycled fuel, such as certain rare earth elements; this would negatively impact economics. Also, pyroprocessing may not be able to separate curium from other transuranic elements; thus, when recycling in thermal reactors, the accumulation of curium, berkelium, and californium would make the recycled material difficult to handle. Therefore, the suitability of pyroprocessing for thermal reactor oxide fuels is unclear, unless a subsequent aqueous processing step is added to recover the desired transuranics in sufficiently pure form. Work is in progress to address these issues.
[4] Fuels containing carbon can accumulate significant inventories of isotope carbon-14, which is produced from nitrogen-16 impurity. There are three options: (1) Reduce the production of carbon-14 by ensuring that only nitrogen-15 is present, since nitrogen-15 is expensive, separation and recycle of nitrogen-15 would be desirable. (2) Recycle carbon-14 to avoid creating new wastes. (3) Dispose of carbon-14 as waste.
[5] Assumes addition of replacement nuclear generating capacity, to keep constant output of 2000 tonne/year and fuel burnup of 50,000 MW-days/tonne.
[6] Uranium from PUREX is high-level waste because of technetium-99. Other newer separation processes are instead tailored to meet U.S. low-level waste criteria.
[7] This waste form may not be borosilicate glass; less expensive waste forms are being developed to take advantage of the low heat load presented by the wastes from this process. For purposes of comparison, an optimistic 30% waste loading in glass was assumed here.
[8] Thermal reactors are more sensitive than fast reactors to the accumulation of neutron-absorbing fission products that accumulate in spent fuel. Pyroprocessing has been shown to adequately remove these elements for fast reactor application, but have not been shown to adequately remove them for thermal reactor use.

In considering compatibility among separation, reactor types, and fuels, note that UREX+ was developed primarily for oxide fuels, which are used in Light Water Reactors (LWR). Pyroprocessing was developed primarily for metal fuels, and is a strong candidate for certain other fuels, e.g., nitride fuels. Options for separating spent nuclear fuel from Gas Fast Reactor and Very High Temperature Reactor (VHTR) fuels have received less attention. UREX+ can be applied to such fuels if a grind-then-leach process is used; pyroprocess is also a candidate. Work is needed to establish strong candidates to separate Gas Fast Reactor and VHTR-type fuels.

Regarding objective 1, reducing burden from waste materials, note the ability of different separation processes to separate transuranic elements, short-lived fission products cesium and strontium, and long-lived fission products technetium and iodine. Separation of transuranic elements from the rest of spent nuclear fuel is required to meet AFCI objectives. It is clear that UREX+ can separate the two classes of fission products. The ability of pyroprocessing to separate cesium and strontium is less established.

Regarding objective 2, improving proliferation resistance, all three of the AFCI processes (UREX+, pyroprocess, and molten salt) avoid separation of plutonium as is inherent with the PUREX process.

Regarding objective 3, energy sustainability, note that the existing ~50,000 metric tonnes of spent nuclear fuel is uranium oxide. Thus, recovery of energy from that spent fuel requires a compatible separation process, with UREX+ being a primary candidate. On the other hand, to enable energy recovery from depleted uranium requires a separation process compatible with fast reactor fuels, with pyroprocessing being a primary candidate.

Regarding objective 4, fuel cycle management, at this level of analysis, all of the AFCI options (UREX+, pyroprocessing, molten salt) appear satisfactory. Continuing progress in researching these options will further clarify safety and economic potential.

In summary, all of the three AFCI options appear to meet the program goals. UREX+ is more developed and therefore less uncertain. Selection among the technologies must be matched with selection among reactor and fuel technologies.

Comparison of Reactor Technologies

Table 3 compares current reactors, advanced reactors (Generation IV), and Accelerator-Driven Systems.

Table 3. Comparison of Reactor Technologies

Reactor Option	Light Water Reactor (LWR)	Very High Temperature Reactor (VHTR)	Super Critical Water Reactor	Molten Salt Reactor	Sodium Fast Reactor	Lead Fast Reactor	Gas Fast Reactor	Accelerator-Driven System	Comment
Strategies Supported									
Once Through	Yes			Yes	---			---	Green = yes White = see details Pink = No
Limited recycle	Yes			Yes	---			---	
Transitional recycle	Yes			Yes	Yes, for the fast reactor component (if any)			Yes	
Sustained recycle	Yes, for the thermal reactor component (if any)			Yes	Yes			---	
Compatible Separation Options									
Aqueous processing, e.g., UREX+	Yes	Requires grind-leach first-step	Yes	---	Yes, if oxide or nitride fuel; No, if metal fuel			---	Green = yes White = see details Pink = No
Pyroprocess	Partial [1]	Yes	Partial [1]	---	Yes			Yes	
Molten salt processing	---			Built in	---			---	
Compatible Fuel Options									
Mixed oxide	Yes			---	Yes	---	Yes	---	Green = yes Pink = No
Inert matrix fuel	Yes			---	---			---	
Americium targets	Yes			---	---			---	
Coated oxycarbide	---	Yes	---	---	---		Yes	---	
Metal	---			---	Yes		---	Yes	
Nitride	---			---	Yes			Yes	
Dispersion	---			---	Yes			---	
Molten fluoride salt	---			Built in	---			---	
Status									
Nuclear Power Plant Generation	I, II, III	These are the six Generation IV concepts.						Not applicable	See definitions in text.
Technology Readiness Level	Commercial experience	Proof of performance	Concept development	Proof of principle	Proof of performance	Proof of principle	Concept development	Proof of principle	See definitions and color code in text.
Objective 1. Reduce the long-term environmental burden of nuclear energy through more efficient disposal of waste materials.									
Potential for transitional or sustained recycle	Yes, with continued uranium enrichment and removal of curium from spent fuel			Yes					Repeated recycle minimizes geological waste.
Reduction of long-term heat load per fuel pass through reactor	1.5-1.8 for inert matrix fuel (no uranium) 1.0-1.2 for mixed oxide fuel (with uranium)			Not defined	1.5			1.7	Higher values allow faster repository benefits.
Objective 2. Enhance overall nuclear fuel cycle proliferation resistance via improved technologies for spent fuel management.									
Destruction rate of transuranic elements, kg/year per MW(th) of capacity	0.31 for inert matrix fuel (no uranium) 0.12 for mixed oxide fuel (with uranium)			Intermediate values depending on spectrum and design	0.24 (conversion ratio = 0.25) 0.0 (conversion ratio of 1.0)			0.28 (conversion ratio = 0.25)	Destruction of transuranics reduces inventory.
On-line versus batch refueling	Batch	On-line (pebble bed variant) or batch (prismatic)	Both	On-line [2]	Batch	Batch (but infrequent in the "battery" design)	Batch		Batch processing may be a proliferation resistance advantage.
Need for uranium enrichment	Yes; indeed, higher burnup requires either higher enrichment (if once-through) or transuranic elements (if recycle)			Not if in fast reactor mode	Generally not			No	Uranium enrichment technology is a potential proliferation pathway.
Objective 3. Enhance energy security by extracting energy recoverable in spent fuel and depleted uranium, ensuring that uranium resources do not become a limiting factor for nuclear power.									
Maximum conversion ratio	0.8			0.8 (once through) to 1.1 (on-line processing) [2]	1.3			< 1	Increased conversion ratio improves use of uranium ore.
Objective 4. Improve fuel cycle management, while continuing competitive fuel cycle economics and excellent safety performance of the entire nuclear fuel cycle system.									
Assists in continuing competitive nuclear energy economics?	Depends on the system in which the technology is used, see Table 1.								Cost of recycling facilities uncertain from insufficient design, licensing info, scale-up, *etc* .
Outlet temperature (^{o}C)	320	850-1000 [3]	550 [3]	700-850 [3]	550 [3]	550-800 [3]	850 [3]	500	Temperatures >850^{o}C allow efficient hydrogen production, higher temperatures improve thermal efficiency
Assists in continuing excellent safety performance	All power, separation, and fuel plants will meet rigorous safety objectives and requirements.								
Fuel processing location	Central plant			On-site	Either on-site or central plant				Multi-faced trade-offs are involved [4]
Requires "wet" storage of discharged fuel	Yes	No	Yes	Fuel not discharged	Depends on reactor design and fuel type, but generally "wet" storage not expected.				Wet fuel storage more vulnerable than dry
Coolant at high pressure	Yes			No			Yes	No	Low coolant pressure is a safety benefit
Coolant is chemically inert	Moderately	Yes	Moderately	Moderately	No	Yes			Coolants that are chemically inactive have a safety benefit
Minimum required cooling time of discharged spent fuel before shipping off-site	Status quo	Lower than LWR because fuel must have higher heat capacity	Similar to LWR	Fuel not shipped off-site	Depends on reactor design and fuel type, expected to be less than or equal to baseline (LWR)				Desire discharged fuel with lower heat-rate and/or higher heat capacity
Color code	Pink = strategies that do not meet each objective			Yellow = strategies that partially meet objective			Green = strategies that meet each objective		

[1] Pyroprocessing may not be suitable for oxide fuels; see footnote 3 of Table 2.
[2] On-line/on-site processing required for high conversion ratio to allow protactinium-233 decay to uranium-233 out of reactor. Burner mode (lower conversion ratio) could be operated batch mode and hence off-site processing.
[3] *A Technology Roadmap for Generation IV Nuclear Energy Systems* , GIF-002-00, December 2002
[4] Relative to central plant processing, on-site fuel processing location would reduce the need for transportation, hence cost, safety, and risk of theft. However, on-site co-location of of processing and power plant may increase proliferation and physical protection concerns by distributing separation technology to more locations. Power plant owners may not wish to additionally operate a co-located processing plant.

The phrase, Generation I, refers to the first nuclear power plants. The *status quo* is the technology used in all U.S. nuclear power plants, Generation II reactors. Generation III/III+ and IV reactors offer the potential for improved performance. The AFCI program must accommodate these potential new reactor types. As indicated in Table 1, some AFCI strategies require development of new reactor types.

"Generation I" experimental reactors were developed in the 1950s and 1960s. "Generation II" large, central-station nuclear power reactors were built in the 1970s and 1980s. This category includes most of the commercial nuclear power plants in the world today, including the 104 licensed in the United States. The vast majority of these are LWRs that use boiling water or pressurized water as their coolants. They extract energy in ways that are similar to power plants that burn coal, natural gas, or petroleum. The difference is that nuclear fission is the source of heat rather than combustion of fossil fuels.

Generation III advanced water reactors were built in the 1990s primarily in East Asia to meet that region's expanding electricity needs. Generation III+ advanced reactors include both water- and gas-cooled reactors with advanced economics and safety, such as the AP1000 and Pebble Bed Modular reactors, which are being proposed as commercial or development projects.

Looking ahead, Generation IV advanced nuclear energy systems are the focus of future R&D.[7] More than 100 experts from twelve countries and international organizations collaborated on selecting the best concepts for Generation IV; these concepts are shown in Table 3. The Generation IV International Forum (GIF) is comprised of member nations that share the goals for future nuclear energy systems. It coordinates member nation research and development programs to magnify the resources available for technology development.

There are six Generation IV reactor concepts that are recommended in the roadmap as having the most promise for meeting the Generation IV goals to improve sustainability, proliferation resistance, safety, reliability, and economics. They also offer the potential to expand the use of nuclear energy beyond electricity generation to include other uses of process heat – especially production of hydrogen. Generation IV nuclear concepts would use gas (VHTR and gas fast reactor), supercritical water, liquid sodium metal, liquid lead metal, or molten salt as coolants. Generation IV options vary significantly in their technological readiness. There have been test power reactors with earlier versions of the gas, sodium, and molten salt coolants. Russian submarines have used lead/bismuth-cooled reactors.

One of the key characteristics of nuclear plants is the energy of neutrons, thermal or fast. Thermal reactors use lower energy ("thermal") neutrons to sustain the fission process. Isotopes that help sustain the fission process in thermal reactors are called "fissile," e.g. uranium-235, plutonium-239, and plutonium-241. The only naturally occurring fissile isotope is uranium-235. Water is commonly used in such reactors for a coolant since the hydrogen contained in water effectively

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[7] *A Technology Roadmap for Generation IV Nuclear Energy Systems*, GIF-002-00, December 2002.

slows down the highly energetic neutrons generated during fission. Virtually all nuclear power plants today are "thermal." Two of the six Generation IV concepts are also thermal reactors – VHTR and supercritical water reactor. (Added to LWRs, this gives three thermal reactor options.) Often, the reactor design and fuel specifics would have to be tailored according to which fuel cycle strategy is adopted.

The molten salt-cooled reactor can be operated as either thermal or fast.

Three of the six Generation IV concepts are fast reactors (sodium, lead, gas coolants). Fast reactors operate with higher energy neutrons and therefore have the potential to sustain the fission process with both fissile (e.g. uranium-235) and fertile isotopes (e.g. uranium-238). The conversion ratio is defined as the amount of new fissile fuel created divided by the amount of fissile fuel consumed, each pass through a reactor. A conversion ratio less than 1 ("burner" mode) means that there is a net consumption of fissile isotopes. A conversion ratio greater than 1 ("breeder" mode) means there is a net creation of fissile isotopes. The fast reactor concepts have some flexibility to shift between these operating modes. Burner mode is appropriate to reduce existing amounts of transuranic elements. Breeder mode is appropriate for a growing fleet of fast reactors so that the creation of new fissile isotopes can supply new reactors. Future system analysis work will clarify the tradeoffs appropriate for scenarios with varying mix of reactors, conversion ratios, *etc*.

Selection among Generation IV concepts depends also on factors beyond direct fuel cycle considerations. For example, concepts with potentially very high coolant outlet temperatures may allow more economic uses of process heat, e.g., for hydrogen production. Also, safety and reliability are critical to current and future nuclear power plants and all plants will continue to meet rigorous safety objectives and requirements. Generation IV plants aim for yet further improved safety characteristics. As the expected design of advanced reactor types is better known, safety indicators can be added to reactor comparisons in future years.

One transmutation option is the Accelerator-Driven System, which provides a different way to transmute isotopes. The energy added to the system from the particle accelerator (via neutrons created from the accelerator target) compensates for the lower content of fissile isotopes. This provides more flexibility to transmute isotopes that are difficult to transmute in reactors, but at the cost of having to supply energy via the accelerator (rather than extract energy from reactors). The Accelerator-Driven System could be used with transitional recycle to replace the role of fast reactors. The remaining degraded plutonium and minor transuranic elements would be sent to the accelerator Driven System for further transmutation. Development of Accelerator-Driven Systems is continuing, primarily in Europe and Japan. Low power experiments have been completed, and several higher power demonstrations are in the design phase.

Regarding objective 1, reducing burden from waste materials, two indicators are shown. Because Table 1 shows that transitional or sustained recycle is important to accomplish this objective, the key technological question is whether each reactor type supports transitional/sustained recycle. The other indicator is the reduction in long-term heat load from each recycle pass through reactors. The "per pass" values apply for the start of recycling; higher values mean that benefits accrue faster. In mixed oxide and fast reactors, the values tend to be sustained for additional recycling passes. For inert matrix fuel, the rapid consumption of fissile isotopes means that fissile isotopes must be added each pass through the reactor and thus the improvement "per pass" depends on how such isotopes are managed and blended.

Regarding objective 2, improving proliferation resistance, the pattern is similar to objective 1. Consider for example the potential destruction rate of transuranic elements: Note the sensitivity of fast reactor transuranic destruction rate to conversion ratio. High conversion ratio or breeder mode improves energy recovery. Low conversion ratio (e.g. 0.25) causes a net destruction of transuranic elements. Fast reactors have the flexibility to adjust to changing needs; they can be modified between 0.25 and 1.0 within the same plant design (cooling system, major buildings, *etc*.). The inside of the main reactor core would have to be changed, at significant cost. Thermal reactors cannot achieve a conversion ratio over 1 because the neutron balance is unfavorable.

Two other reactor-specific factors require mention, although their importance to overall proliferation resistance requires clarification. First, reactors vary regarding the ability to refuel on-line (while the reactor is operating) or only batch (requiring reactor shutdown). Batch processing could be a significant proliferation resistance advantage because removal of fuel from the reactor would require reactor shutdown. Second, once a system of fast reactors is established, they do not require uranium enrichment, which is a technology that has been used by nations to acquire weapons grade uranium.

Regarding objective 3, energy sustainability, when operating in breeder mode, fast reactors offer the potential to radically extend uranium ore supplies by creating more fissile isotopes than they consume ("breeder" mode). This makes all natural uranium (0.7 percent uranium-235 and 99.3 percent uranium-238) useful as fuel.

Regarding objective 4, one key discriminating characteristic is the maximum potential outlet temperature. The VHTR option appears to provide the highest potential outlet temperature and, hence, potential for greater thermal efficiency and hydrogen production. The SCWR, on the other hand, is likely to face more modest materials challenges and offer passive safety features.

Future work is needed to explore the potential for attractive mixes of reactor types

Comparison of Transmutation Fuel Technologies

Table 4 compares several transmutation fuel technologies with regard to technical maturity and the AFCI objectives. Fuels literally link the various parts of the fuel cycle – nuclear power plant, separation facility, fuel fabrication plant, and ultimate waste disposal. Therefore, the options for fuels and these fuel cycle facilities must work together. This also means that quantification of fuels against AFCI objectives generally requires specifying either the reactor in which they are to be used, or the separation process to be used, or both.

Table 4. Comparison of Transmutation Fuel Technologies

Transmutation Fuel Option [1]	Transuranic mixed oxide fuel	Inert matrix fuel with transuranics	Americium targets	TRISO with transuranics (carbide, oxycarbide)	Metal (fast reactor fuel)	Nitride (fast reactor fuel)	Oxide (fast reactor fuel)	General Dispersion CERCER (ceramic/ceramic), CERMET (ceramic/metal)	Comment
Strategies Supported									
Once through	---				---			---	
Limited recycle	Yes				---			Yes	Green = Yes White = see details Pink = No
Transitional recycle	Yes				Yes, for the fast reactor component (if any)			Yes	
Sustained recycle	Yes, for the thermal reactor component (if any)			Yes	Yes			Yes	
Compatible Separation Options									
Aqueous processing, e.g., UREX+	Yes			Requires grind-leach first step [4]	---	Yes	Yes	Yes	Green = Yes White = see details Pink = No
Pyroprocess	Partial [5]	---	---	Yes	Yes	Yes	Partial [5]	---	
Compatible Reactor Options									
Light Water Reactor (LWR)	Yes			---	---			Yes	
Very High Temperature Reactor (VHTR)	Yes			Yes	---			---	Thermal reactor options
Supercritical Water Reactor	Yes			---	---			---	
Sodium Fast Reactor	Yes	--- [2]	--- [3]	---	Yes			Yes	
Lead Fast Reactor	---			---	Yes		---	Yes	Fast reactor options
Gas Fast Reactor	---			Yes	---	Yes		Yes	
Accelerator Driven System	---			---	Yes			---	
Status									
Technology Readiness Level	Concept development [6]	Concept development	Ready to start proof of principle		Early proof of principle			Concept development	See definitions and color code in text.
Experience with uranium	Extensive	Not applicable (no uranium)		Extensive		Some			
Experience with plutonium	Some	Little	Not applicable	Some	Extensive	Little	Some		Confidence increases as the fraction of Np-Am-Cm in fuel decreases.
Experience with Np, Am, Cm	Little		Some	Little	Some	Little			
Objective 1. Reduce the long-term environmental burden of nuclear energy through more efficient disposal of waste materials.									
Allows recycle of transuranic elements	Yes, but inefficient (uranium produces more transuranics)	Yes, efficient (no uranium to produce more transuranics)	For americium only	Yes, efficient	Yes, very efficient				Transuranic isotopes typically dominate repository long-term heat and estimated dose.
Suitable form for repeated recycling	Yes	Depends on matrix material [7]	Yes	If recycling is needed, materials and technology must be developed and tested	Yes			Potentially yes, but an effective matrix material has not been decided yet	Some inert matrix fuels and carbides are difficult to recycle.
Reduction of long-term heat load per fuel pass through reactor	1.0-1.2	1.5-1.8	Should be high	1.5-1.8 without uranium 1.0-1.2 with uranium	1.5				The higher the better.
Maximum expected burn-up (MW-day per kg of initial heavy metal)	50-100	550	Not applicable	Stable fuel for very high burnup	250	500	Stable fuel for very high burnup		Higher burnup decreases the waste volume and mass generated per MW-day.
Suitable waste form if not recycled	Same as baseline (uranium oxide fuel)	Depends on matrix material [7]	Yes, probably better waste form than baseline		To be assessed. Fast reactor fuels are being designed for repeated recycling.				Important if wish to stop recycling so that used fuel could be sent directly to a repository.
Objective 2. Enhance overall nuclear fuel cycle proliferation resistance via improved technologies for spent fuel management.									
Reduces weapons-usable inventory	Yes, but inefficient	Yes, efficient	Efficient for americium	Yes, efficient					Pattern similar to recycling of transuranics (objective 1)
Objective 3. Enhance energy security by extracting energy recoverable in spent fuel and depleted uranium, ensuring that uranium resources do not become a limiting factor for nuclear power.									
Enable energy recovery from legacy spent fuel	Yes		Can only recover the energy in americium	Yes					
Enable energy recovery from depleted uranium?	No, but see fast reactor analog	No		Yes					
Objective 4. Improve fuel cycle management, while continuing competitive fuel cycle economics and excellent safety performance of the entire nuclear fuel cycle system.									
Assists in continuing competitive nuclear energy economics?	Depends on the system in which the technology is used, see Table 1.								Key issue is the incremental costs relative to existing once-through, PUREX separation, and Pu-mixed oxide fabrication.
Assists in continuing excellent safety performance	All power, separation, and fuel plants will meet rigorous safety objectives and requirements.								The composition of transuranics in fuels is controlled so it can be used safely in each reactor type.
Requires wet storage of discharged fuel	Yes		Likely	No	Depends on reactor type and design, but generally wet storage not expected.				Wet fuel storage has higher vulnerability to contaminate water than dry storage.
Minimum required cooling time of discharged spent fuel before shipping off-site	Baseline (5 years)		Likely same or higher than baseline	Likely lower (faster) than baseline	Depends on reactor type and design, but expected to be less than or equal to baseline.				Desire discharged fuel with lower heat-rate and/or heat capacity.
Color code	Pink = strategies that do not meet each objective				Yellow = strategies that partially meet objective			Green = strategies that meet each objective	

[1] Table only includes fuels that can transmute one or more transuranic elements; therefore, current uranium oxide fuel and TRISO without transuranics are not shown. TRISO is a fuel type developed for high-temperature reactors; it stands for Tri-material ISOtropic composite coating applied to fuel particles. The molten salt reactor fuel-coolant is not shown; it is addressed in Table 3.
[2] There would appear to be little reason to use inert matrix fuel in fast reactors because it is aimed at reducing transuranic inventory via dedicated targets.
[3] There is little value in using separate americium targets in fast reactors as all transuranics will transmute adequately in a single fuel type; also, the likely separation technique (pyroprocessing) would not separate americium from other transuranic elements. Separate americium targets could be a more efficient way to transmute americium in thermal reactors than including americium in a fuel.
[4] Fuels containing carbon can accumulate significant inventories of isotope carbon-14, which is produced from nitrogen-16 impurity. See footnote 4 of Table 2.
[5] The suitability of pyroprocessing for oxide fuel is unclear, see footnote 3 of Table 2.
[6] Plutonium mixed oxide fuel (without neptunium, americium, or curium) is commercial in France. The U.S. program instead focused on transuranic mixed oxide, to avoid separation of pure plutonium and to ensure transmutation of americium. Outside of the AFCI, the United States is also using plutonium mixed oxide to consume excess weapons-grade plutonium.
[7] For Inert matrix fuel, the matrix options include magnesium-zirconium oxide (recyclable), zirconium oxide (difficult to recycle), silicon carbide (difficult to recycle)

Regarding objective 1, reducing burden from waste materials, the ideal fuel would have high burnup, greatly reduce long-term heat load in a repository, support transitional/sustained recycle, and be able to be used in a wide range of reactor types. Mixed uranium plus transuranic oxide fuels for LWRs (or their TRISO[8] analogs for VHTRs) perform relatively poorly in terms of reduction of long-term heat load. Transuranic-only (no uranium) fuels for LWR (or their TRISO analogs for VHTRs) are relatively poor in terms of supporting transitional/sustained recycle. Fast reactor fuels (metal, nitride, oxide, dispersion) are being developed only for fast reactors.

Regarding objective 2, improving proliferation resistance, the table shows that the fuels (inert matrix fuel, fast reactor fuels) that best consume transuranic elements are naturally the same ones that best reduce the weapons-usable inventory.

Regarding objective 3, energy sustainability, any of the fuels (except the specialty case of Am targets) can use transuranic elements recovered from legacy spent fuel. Only the fast reactor fuels can enable energy recovery from depleted uranium.

Fuel performance against objective 4 generally requires specification of reactor type and design.

[8] TRISO is a fuel type developed for high-temperature reactors; it stands for Tri-material ISOtropic composite coating applied to fuel particles.

IV. STATUS OF ADVANCED FUEL CYCLE INITIATIVE RESEARCH

This section presents the significant accomplishments of the AFCI supporting the United States' progression to a sustainable nuclear energy future. The highlighted program achievements make measured progress towards closing the nuclear fuel cycle and assuring a secure, reliable, and environmentally advantageous source of energy for the nation. The AFCI research efforts are organized in four technical areas: Systems Analysis, Separations, Transmutation, and Fuels, which correspond (in order) to Tables 1, 2, 3, and 4. Notable accomplishments in university collaboration are also presented. The section ends with planned future major milestones.

Systems Analysis

Systems Analysis bridges and integrates the program technical areas and provides the models, tools, and analyses required to assess the feasibility of design and deployment options and inform key decision makers. The systems analysis activity is conducted jointly with the Generation IV Program. Accomplishments include:

- Clarifying and articulating the range of AFCI objectives, as outlined in this and other reports.
- Evaluating the range of options against the range of objectives, as outlined in this and other reports.
- Examining the implications of different mixes of reactors and impact of deployment of different technologies, as well as potential "exit" or "off ramp" approaches to phase out technologies if the need arises.
- Evaluating the capability of various reactor systems to handle transmutation, including extended burnup of plutonium in LWRs and gas-cooled reactors, potential for destroying other transuranic elements in LWRs, and consumption of transuranics in fast reactors and Accelerator-Driven Systems.
- Assessing the benefits of advanced fuel cycles to reduce the need for additional geological waste repositories and to more efficiently use the first repository.
- Performing dynamic simulations of fuel cycles to quantify infrastructure requirements, identify key trade-offs between alternatives, and examine the ramifications of shifts from one reactor type to another.
- Evaluating repository characteristics such as volume, mass, and heat load; in comparison of various fuel cycles, reactor facility requirements, and economics.

Separations

AFCI separations research focuses on both the near-term fuel cycle and future Generation IV systems. Separations research includes both advanced aqueous processing and non-aqueous technology. Advanced aqueous processing focuses on the UREX+ process, while non-aqueous processing has been concentrated on the pyroprocessing electrometallurgical technique. Accomplishments include:

- Laboratory-Scale UREX+ Demonstration – UREX+ is an advanced aqueous solvent extraction process under development for the treatment of commercial LWR spent fuel. It is also a candidate for some of the Generation IV reactor fuels, see Tables 2 and 4. Laboratory scale multi-step separation from irradiated fuel has been demonstrated. Key enhancements to UREX+ are in process. All required steps have been shown to work at laboratory scale.

  – UREX – AFCI has demonstrated at laboratory-scale separation of uranium at sufficient purity so that the uranium could be disposed under U.S. near-surface burial regulations.
  – UREX+ Solvent Extraction Hot Tests – Laboratory-scale demonstration of the uranium/plutonium/neptunium co-extraction process has been completed using radioactive test materials. This avoids separation of plutonium by itself.
  – Americium and curium separation – UREX+ group separation of these transuranic elements has been demonstrated at laboratory scale.
  – Actinide Crystallization Process – "Actinides" include uranium and transuranics. This process is a possible front-end for separation of uranium prior to UREX+ extraction, greatly reducing the quantity of liquid to be processed. Bench-scale tests have been completed and a crystallizer of sufficient size is being built to obtain data applicable to a full-scale unit.
  – Advanced Uranium/Transuranic Recovery – Operation of fully integrated electrolysis equipment has been successfully demonstrated, with future efforts considering definition of operating parameters and a design concept for a commercial-scale electrolysis cell.
  – Cesium-Strontium Extraction Process Development – Laboratory-scale demonstration of a process for separation of cesium and strontium (chlorinated cobalt dicarbollide/polyethylene glycol-based solvent extraction) has been accomplished. Laboratory-scale demonstration of an alternative (calixarene/crown ether solvent process) has been initiated with initial promising results.
  – Technetium and iodine separation – Laboratory-scale demonstration of processes for separation of these long-lived fission products has also been accomplished.

- PYROX Process Development – The pyrochemical reduction (PYROX) process is being developed for treatment of Generation IV oxide fuels. High-capacity reduction experiments and improvements in cell design have been completed.

- Pyroprocessing demonstration – Pyroprocessing is an advanced electrochemical separation technique for metal fuels; it is also a candidate for other Generation IV fuel types, see Tables 2 and 4.

  – EBR-II Fuel Electrometallurgical Treatment – The existing Experimental Breeder Reactor-II (EBR-II) driver fuel contains elemental sodium, which is not acceptable for direct repository disposal. A treatment rate of 159 kilograms/year has been reached, i.e., more than laboratory-scale.
  – As noted in Table 2, separation among transuranic elements has not been demonstrated and is probably not possible.
  – As shown in Table 2, separation of cesium and strontium has not yet been demonstrated.

– Technetium and iodine separation – Laboratory-scale demonstration of processes for separation of these long-lived fission products has also been accomplished.

- New Engineered Product Storage and Disposal – In AFCI scenarios, various materials must be put into long-term storage or permanent disposal.

  – For cesium-strontium, storage forms based on glass and zeolite are being assessed, together with appropriate storage containers.
  – For americium-curium, a pure curium oxide has been rejected due to fabrication issues while co-storage with plutonium-neptunium appears attractive.
  – For residual high-level waste, laboratory-scale tests support qualification of a ceramic waste forms by characterizing degradation behavior, developing models to calculate long-term degradation behavior under repository conditions, and confirming the applicability of models.

Transmutation

Transmutation is the process of transforming one nuclide into another via neutron-induced fission or capture, to reduce isotopes in spent nuclear fuel that dominate the issues of nuclear material management and waste disposition. Transmutation can occur in LWRs, Generation IV thermal reactors, fast reactors, Accelerator-Driven Systems, or some optimized combination of these systems. The transmutation effort also addresses materials issues associated with advanced fuels and coolants. Accomplishments include:

- Cross-Section Measurements for transuranic elements – Accurate measurement of fission and capture cross-sections are needed to support transmutation calculations and transmutation fuels development. Np-237 fission cross-section data have been updated.
- DELTA Loop Corrosion Tests – Technology development is centered on a lead-bismuth test loop, in which 1000-hour corrosion tests at temperatures up to 550ºC on a large matrix of materials have been completed. Test specimen analysis showed the efficacy of oxygen control in mitigating corrosion, and indications of silicon and chromium alloying enhancing corrosion resistance by forming stable and protective oxides.
- Radiation Damage Modeling – Improved understanding of radiation damage to reactor and fuel materials is being developed. Characterizations of defect migration, helium migration, and helium trapping were used to develop a probabilistic 3-dimensional code to simulate radiation-induced point defects.
- TRIGA[9] Accelerator-Driven Experiment (TRADE) – The scheduled TRADE source multiplication experiments were successfully completed. The sub-criticality levels for several TRIGA configurations were calculated and compared against experimental values.

[9] TRIGA is a registered copyright of General Atomics; it stands for Training, Research, Isotopes, General Atomics.

Fuels

AFCI fuels development includes proliferation-resistant fuels for LWRs, fuels that will enable transmutation of transuranics in Generation IV reactors, and all fuels for the fast reactor group of Generation IV reactors. Accomplishments include:

- Mixed Oxide Fuels – Mixed oxide (uranium, plutonium, neptunium) fuels are being developed for LWRs to demonstrate thermal spectrum burning of transuranics.
- FUTURIX Collaboration – FUTURIX is a collaborative experiment in which nitride and metal fuels containing plutonium, neptunium, and americium will be fabricated in the United States, assembled in Germany, irradiated in France, and finally shipped back to the United States for post-irradiation examination and separations testing.
- Metal Fuels – Efforts have focused on providing small samples of metal fuels with well-characterized microstructures for irradiation testing, with experience gained in fabricating small samples providing a basis for developing large-scale fuel manufacturing processes in subsequent years.
- Nitride Fuels – Development is continuing on nitride fuels capable of high burnup, easily fabricated in a remote environment, and exhibiting benign behavior during reactor steady-state and off-normal events.
- Advanced Test Reactor Irradiation Tests – Irradiation performance data from ongoing tests of fuel capsules will be combined with physical, thermal, and chemical property data to develop models of the complex behavior of fuels.

University Collaborations

The AFCI supports university research and funds fellowships for students in nuclear engineering. AFCI supports directed research at a number of universities, and has dedicated University Programs with (1) the University of Nevada at Las Vegas in advanced radiochemistry, materials, and transmutation technologies, (2) the Idaho Accelerator Center in Pocatello Idaho for facilities used in research and education in charged particle accelerator applications in nuclear and radiation science, and (3) the University Research Alliance, managing the Fellowship Program supporting students in disciplines related to transmutation research and technology development.

Future Objectives

The AFCI is focused on research and development supporting the advanced fuels and fuel cycles for Generation IV, and informing the Secretary's report to Congress in the 2007-2010 timeframe on the technical need for a second repository. High priority AFCI program objectives over the next ten years include:

- 2008 – Provide engineering data and analysis to support the Secretary's report to Congress on the need for a second repository.

- 2010 – Quantitatively define feasible nuclear fuel cycle options and technologies for implementation, and develop fuel cycle technologies that enable evolution to a stable, long-term advanced fuel cycle.
- 2015 – Provide engineering data to recommend the best option for nuclear waste management and obtain sufficient information to begin near-term implementation.
- 2015 – Provide engineering data and analysis for a recommendation of the best option for an advanced nuclear fuel cycle incorporating Generation IV technology.

V. SUMMARY

Selection and optimization among fuel cycle strategies and technologies is complex. This summary is divided into three subsections – what is needed to meet the first three AFCI objectives (waste management, proliferation resistance, energy sustainability), what is needed to meet the fourth AFCI objective (economics, safety, system management), and what is required to progress from the *status quo* to various recycle strategies.

Waste management, proliferation resistance, and energy sustainability

The once-through fuel cycle cannot be advanced much further in terms of the first three AFCI objectives. At best, high burnup fuels can provide 20 percent improvements to geologic repository needs and energy sustainability. At growth rates of 0.0, 1.8, and 3.2 percent per year, four to twenty geologic repositories would be required this century, assuming each was limited to 70,000 metric tonnes. U.S. technological advances in the once-through fuel cycle would lead to little or no improvements to proliferation resistance because a quarter-century of data indicate that it will not discourage international recycling of plutonium and because uranium enrichment needs will remain. (The need for uranium enrichment actually increases slightly with higher burnup.)

As one progresses through the recycle strategies – limited recycle, transitional recycle, sustained recycle – the AFCI objectives for waste management, proliferation resistance, and energy sustainability are increasingly met. There are four major "breakpoints":

- Limited recycle starts the draw-down of weapons-usable material and starts accruing improvements for future geologic repositories, waste management and energy sustainability that are at least as significant as high burnup within once-through fuel cycle.
- Transitional recycle achieves the key AFCI objective to avoid the need for a second geologic repository until the next century, ensuring that repository space resources do not become a limiting factor for nuclear energy. Transitional recycle also converts transuranic elements from waste management liabilities into energy resource assets.
- Sustained recycle converts waste from both enrichment (depleted uranium) and spent fuel from liabilities into energy resource assets, thereby using up to 99 percent of the energy content in original uranium ore and ensuring that uranium resources do not become a limiting factor for nuclear energy.

Economics, safety, and system management

There are three major economic uncertainties. 1) The cost of and options for future geologic repositories are an uncertainty for the once-through and limited recycle strategies. 2) The cost of Generation IV fast reactors is also unknown, but is being studied. Fast reactors are critical to sustained recycle. Fast reactors may be required for transitional recycle, but, if so, their impact on overall economics is muted because they would probably be limited to 10-20 percent of the reactor fleet. 3) The cost of new recycle fuels and associated separation plants is uncertain, but is being studied. Table 1 (page 16) shows the various trends. The approach of transitional recycle with only thermal reactors (no fast reactors) has relatively low economic uncertainty, but there are significant technical issues with such an approach.

There are two major safety uncertainties. 1) The safety of new reactor types must be demonstrated. 2) The impact of new fuels on reactor safety performance must be ensured

Once the technologies are available (not for decades), all of the recycle strategies have the potential to accelerate removal of spent fuel from power plants.

Getting from here to there

All options except the *status quo* require research and development.

Consider the technology readiness rows in Table 1. Benefits from research and development are cumulative. With few exceptions, each new technology that is demonstrated and implemented continues to provide benefit later, if additional technologies become available.

- Recyclable transuranic mixed oxide and recyclable transuranic inert matrix fuel start providing benefits with limited recycle (even if recycling does not proceed further) but also provide benefits in transitional recycle. They may cease to be used if sustained recycle is adopted.
- UREX+ is used for limited recycle, transitional recycle, and possibly sustained recycle (depending on fuels used for sustained recycle).
- Advanced thermal reactors and their associated fuels do not adversely impact the fuel cycle – provided the fuels are recyclable.
- Implementation of fast reactors and associated fuels would make transitional recycle easier (because they do not have the curium problem) and enable sustained recycle.
- The only technology potentially used for limited recycle that would not be applicable for transitional or sustained recycle would be new non-recyclable fuels, such as non-recyclable forms of inert matrix fuel.

While greater benefits are obtained by achieving the more advanced fuel cycle strategies further to the right in Table 1, the technical readiness of these approaches are generally less mature. Many of the necessary technologies are only in the concept development or proof of principle stages. At these stages, most research is bench scale, and therefore relatively inexpensive. Maturation through proof of performance research will typically require scale-up research and engineering before the technologies can be fielded and the advanced fuel cycles achieved.

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Appendix A

Language Accompanying the Fiscal Year 2003 Appropriation

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Excerpt from House Report 108-10

"*Advanced Fuel Cycle Initiative*...

"...In order to ensure that the Department's AFCI can lead to useful and practical technologies, the Office of Nuclear Energy, Science and Technology is directed to provide Congress with an annual AFCI Comparison Report. The report will provide qualitative and quantitative information to enable Congress to compare the various technology approaches to managing commercial spent fuel. The first such report is due by May 30, 2003, and should be updated each year thereafter so long as the Department continues its AFCI research activity. This report should include comparison matrices that contrast the advantages and disadvantages of possible fuel treatment and advanced fuel cycle technologies. The technologies should be evaluated with respect to energy and chemical inputs, product and waste stream outputs, proliferation considerations, estimated R&D and facility life cycle costs (i.e., capital, operating, and D&D plus disposal of wastes), and the estimated number and type of facilities required. If the Department cannot provide specific, quantitative information (such as for yet-to-be developed technologies), it should identify in the matrices the estimated dates by which ongoing R&D will provide the answers. Today's commercial light water reactor fuel cycle and spent nuclear fuel disposition should be used as the basis for comparison and to bound and define performance objectives for the new technologies.

"One matrix should compare spent fuel treatment technologies, comparing advanced fast reactor systems, accelerator systems, and other existing and proposed reprocessing and transmutation technologies (e.g., PUREX, UREX, UREX+) against the current once-through approach with spent fuel from light water reactors. The second matrix should include a similar contrast of the advantages and disadvantages and facility requirements for advanced fuel cycles, and should specifically address the six innovative reactor concepts that the member countries of the Generation IV International forum have agreed to pursue. The second fuel cycle matrix should also include consideration of thorium-uranium and thorium-plutonium fuel cycles and the gas turbine modular helium reactor...."